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# Life Modeling for Nickel-Hydrogen Batteries in Geosynchronous Satellite Operation

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**14. ABSTRACT**

A model for predicting nickel-hydrogen battery lifetime in LEO applications has been extended to the conditions encountered in GEO orbiting satellites. The model has been found to accurately reproduce the lifetimes observed from available accelerated GEO tests, and is also consistent with the existing orbital performance data.

The model has been used to predict how properly designed and operated nickel-hydrogen battery lifetimes should depend on the operating environments and charge control methods typically used in GEO operation. Lifetime is found to be strongly dependent on DOD (particularly at high operating DOD levels), amount of overcharge, trickle-charge rate, and operating temperature. In addition, the model finds a strong coupling between these wear-controlling parameters. The model suggests that with an optimized charge control system and optimized operating conditions, properly designed nickel-hydrogen batteries are capable of reliably providing over 30 years of GEO operation at a DOD of 70–75%. The results also indicate that careful optimization of charge control, operating temperature, and the maximum required DOD are needed to guarantee reliable operation beyond 10 years.

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# 1. Introduction

Understanding and predicting the lifetime of nickel-hydrogen batteries that are used in satellites has been traditionally done through the use of long-term life test programs that attempt to test the battery cells on the ground just as they are flown in satellites. This is often difficult to do since today's satellites are often expected to last for 15 years or more, but are developed and built in only several years with very little additional long-term life testing of the nickel-hydrogen batteries. In this situation, the expected battery lifetime must be determined based on an appropriate analysis of the data that have been accumulated over many years of both testing nickel-hydrogen batteries and operating them within satellites in space.

One general method for converting the nickel-hydrogen cell test database into a predictive model that can be used to understand how battery life is influenced by the operational conditions in space is to develop a wear-out model that specifically includes each factor that is known to contribute to cell wear. This has been done[1] using a multiple linear regression analysis of the available test data to determine the sensitivity of cell lifetime to each of a number of factors that are thought to contribute to an accelerated cell wear rate. These stress factors are:

- Depth of discharge
- Temperature
- Amount of excess overcharge (above that needed to offset self-discharge)
- Overcharge rate (expressed as peak cell recharge voltage above 1.52 V)
- Calendar life
- Initial wear from cell storage

Such a linear regression analysis was performed in Ref. 1 for two types of failures observed in test cells: failure by gradual capacity loss and failure by the more sudden formation of a cell short circuit. Coefficients for each of the stress factors is determined as a function of time during cell operation, thus allowing the regression equations to be used for predicting battery lifetime. Furthermore, the model can predict whether failure is more likely as a result of a cell short circuit, or as the result of capacity loss. The failures predicted by this model are only those related to normal wear processes, and do not include those from improper cell or battery design, fabrication, or charge control issues.

The model described above has proven to be quite accurate for predicting the lifetime of cells in a wide range of low-earth-orbit (LEO) life tests that were not used as a source of data in developing the model. Typical accuracy in predicting life was within about ±10% of the observed lifetime for such LEO nickel-hydrogen battery tests.[1] However, it was not at all clear from this earlier work how the model could be extended to predict the lifetime of a nickel-hydrogen battery operating in a geosynchronous regime, or whether such an extension of the model was possible. Geosynchronous opera-

tion (GEO) typically involves 88 eclipses per year, with much greater peak DOD than in LEO. Once the battery is recharged, the rest of the time is typically spent on trickle charge to maintain all the cells at a high state of charge.

The stress factors described above are also expected to be operative in GEO to cause the gradual degradation and eventual failure of nickel-hydrogen cells. However, in the GEO environment these stress factors can have a different significance in controlling battery life than they do during LEO operation. Depth of discharge is typically significantly higher in GEO applications, thus leaving less margin to accommodate cell degradation. However, the actual stress resulting from cyclic discharge and recharge is expected to be much less because GEO cycling involves only 88 cycles per year. In addition, because charge rates are typically low in GEO, the factor of overcharge rate is expected to contribute little to accelerated cell wear out. However, because GEO satellite applications can last longer than 15 years, calendar life degradation will tend to be more significant than in LEO. Operating temperature is expected to be an important variable affecting wear rates, just as it is in LEO applications.

The greatest uncertainty in the application of a wear model such as that of Ref. 1 is in how overcharge contributes to cell wear in GEO. Analysis of the LEO databases for nickel-hydrogen cells has separated the wear resulting from overcharge into two contributions: one from the Ah amount of overcharge in excess of that needed to just compensate for self-discharge, and one from the overcharge rate based on the cell voltage relative to 1.52 V. In LEO orbits, the amount of excess overcharge is typically relatively low, but the overcharge usually occurs at rates high enough to bring cell voltages up to 1.52 V or more. In GEO orbits, however, the total amount of excess overcharge can be quite high, but much of that overcharge is at trickle charge rates that maintain overcharge cell voltages well below 1.52 V. This is particularly true during GEO solstice seasons, where the batteries can be kept on continuous trickle charge for long periods of time. Thus, for GEO solstice simulations when the batteries are on trickle charge, the model of Ref. 1 will typically predict a negative stress contribution from the overcharge rate, in conjunction with a positive stress contribution from the total excess Ah of overcharge. The only requirement for physically reasonable overcharge stress in the model is that the total stress from these two contributions must remain above zero at all times.

Because the model does allow negative stress from low overcharge (trickle charge) rates to partially compensate for the stress resulting from the excess Ah of overcharge, it is possible to have a very low wear rate in GEO while still maintaining good capacity with trickle charge rates that may be 2–3 times the self-discharge rate. This approach to modeling wear during GEO operation provides a quantitative method for capturing the known stress factors, particularly in comparison with the assumption often made in accelerated testing that trickle charge is always a zero-wear condition.

In this report, we will correlate the wear rates determined from the model of Ref. 1 with the actual experience with nickel-hydrogen batteries in GEO operation, and thus determine whether the data show that the assumptions in the wear model need to be adjusted to properly describe the trickle charge stress levels, or wear from other factors experienced in GEO. These correlations will allow a validated GEO wear model to be developed. This model will be used to examine the typical life-limiting factors expected for GEO operation of nickel-hydrogen batteries.

## 2. Validation of a GEO Wear Model

The model of Ref. 1 has already been found to predict the life of nickel-hydrogen cells in LEO cycling conditions with an accuracy of about ±10%. The first and simplest approach to modeling GEO nickel-hydrogen cell life is to use this model with no changes. If the available performance data correlate well with the model predictions, then no adjustments to the model are warranted, and it can be used as is.

The one portion of the model of Ref. 1 that needs to be expanded for use in GEO predictions is the behavior of cells during periods of trickle charge, when the peak voltage must be predicted as a function of trickle charge conditions. When simulating actual battery data, the actual daily-average trickle charge voltages can be used for the peak voltage in the model. However, in making predictions in the absence of data, the typical correlations shown in Figure 1 between voltage and trickle charge rate at different operating temperatures are required. In this figure, the level associated with zero stress from the peak charge voltage (or overcharge rate) is shown at 1.52 V. Trickle charge at lower currents or at higher temperatures can thus provide reduced wear rates to partially offset the wear resulting from the excess overcharge. At a trickle charge rate below 0.004C, there is little wear from overcharge simply because the trickle charge rate is not much above the self-discharge rate.

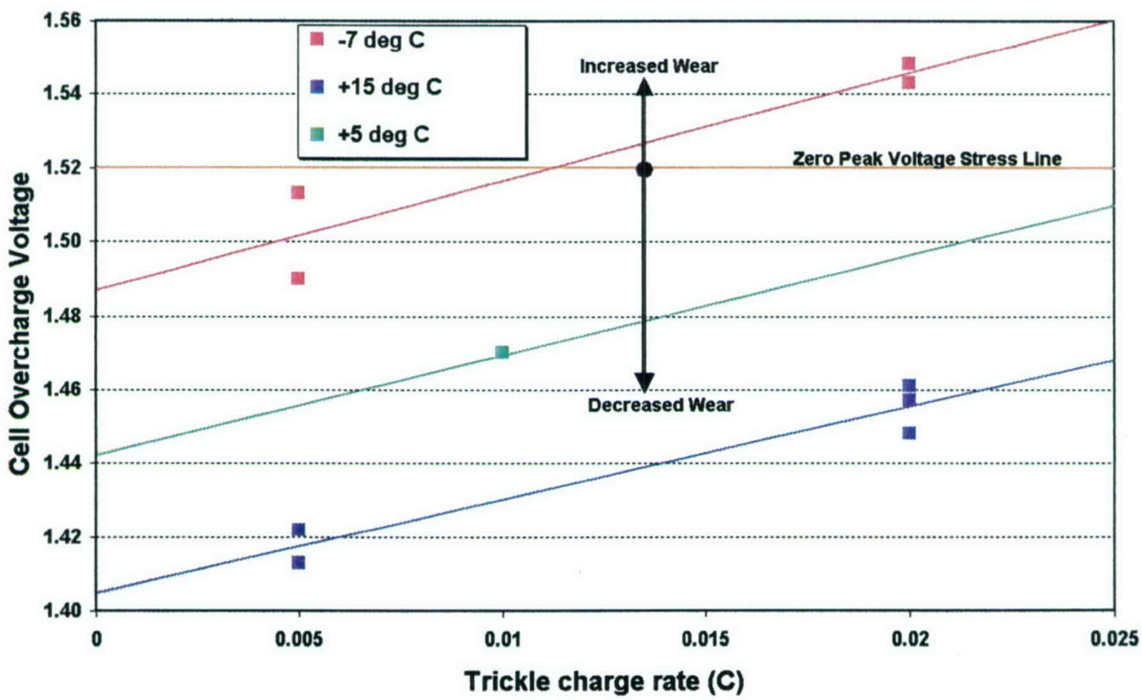


Figure 1. Typical correlations between cell overcharge voltage and trickle charge rates at various operating temperatures for nickel-hydrogen cells.

The GEO performance database for nickel-hydrogen batteries consists primarily of accelerated ground tests and real-time operation in satellites. The only known wear-related failures are in accelerated ground tests, as will be described in the following sections. Nickel-hydrogen batteries continue to operate in a number of space missions as will also be discussed; therefore, the orbital experience provides only lower limits on battery life for correlation with the model predictions.

## 2.1 Accelerated GEO Test Correlations

Most GEO ground tests of nickel-hydrogen cells are run under accelerated conditions where most or all of the two annual 5-month solstice periods is eliminated, and the batteries are exposed to repeated 44-day eclipse seasons. Numerous examples of such tests have been run in excess of 40 eclipse seasons without experiencing cell failure. In a few instances, battery cell failure has been seen in these life tests.

The first life test that will be discussed here involved a nine-cell pack of 4.5-in.-dia nickel-hydrogen cells. At the –5°C temperature at which these cells were charged, they had a capacity that exceeded the nameplate capacity by about 10%. The cells were cycled at 91.6% DOD based on nameplate capacity, or 82% DOD based on the –5°C capacity. The cells were recharged after each discharge at about a C/12 rate to a charge return ratio of 1.25, and then put on a C/100 trickle charge until the next eclipse discharge. A 15-day solstice period was used between each 44-day eclipse season, with about a 35% DOD cycle occurring each day during the solstice period. In addition, this test experienced an anomaly after eclipse season 20 that involved the application of a continuous C/20 overcharge for about 90 days. The cells were put back on test after this anomaly, and continued to perform acceptably, although there was a noticeable drop in performance. After 26 seasons on test, one of the cells fell below 1 V, thus indicating failure as a result of insufficient usable capacity.

The timeline from this 9-cell test can be simulated using the wear model of Ref. 1. Figure 2 shows the accumulated wear predicted by the model for these test conditions. Of interest is the predicted ~50% wear contributed by the test anomaly. While this may seem like an extreme contribution from an anomaly of this kind, when it is added to the normal wear accumulated during the test, the first cell failure is predicted to occur during eclipse season 27. This is quite good agreement (well within 10%) with the first observed cell failure during eclipse season 26. Not only does the model accurately predict life in this instance, but also correctly predicts that failure is almost certain to occur as the result of capacity loss rather than the formation of internal cell short circuits. Thus, the wear model appears to be applicable without any significant modification to the conditions of accelerated GEO ground tests typically used for nickel-hydrogen cells.

Typical accelerated GEO ground tests do not involve the test anomaly indicated in Figure 2, and also do not show cell failure as early in life as was seen in the test of Figure 2. Another example of a life test that involved six 4.5-in.-dia nickel-hydrogen cells was run for 30 accelerated seasons with no cell failures. The peak DOD was 91.2% based on the nameplate cell capacity, and 80% based on the actual –5°C capacity, which is the temperature at which the cells were charged. The full recharge rate was about C/15, and the recharge fraction each cycle was 1.30. After recharge to this recharge fraction, a C/100 trickle charge rate was maintained until the next eclipse discharge. This test was operated for 30 eclipse seasons before being terminated with all cells still operating (the lowest cell was at 1.05 V for the longest eclipse).

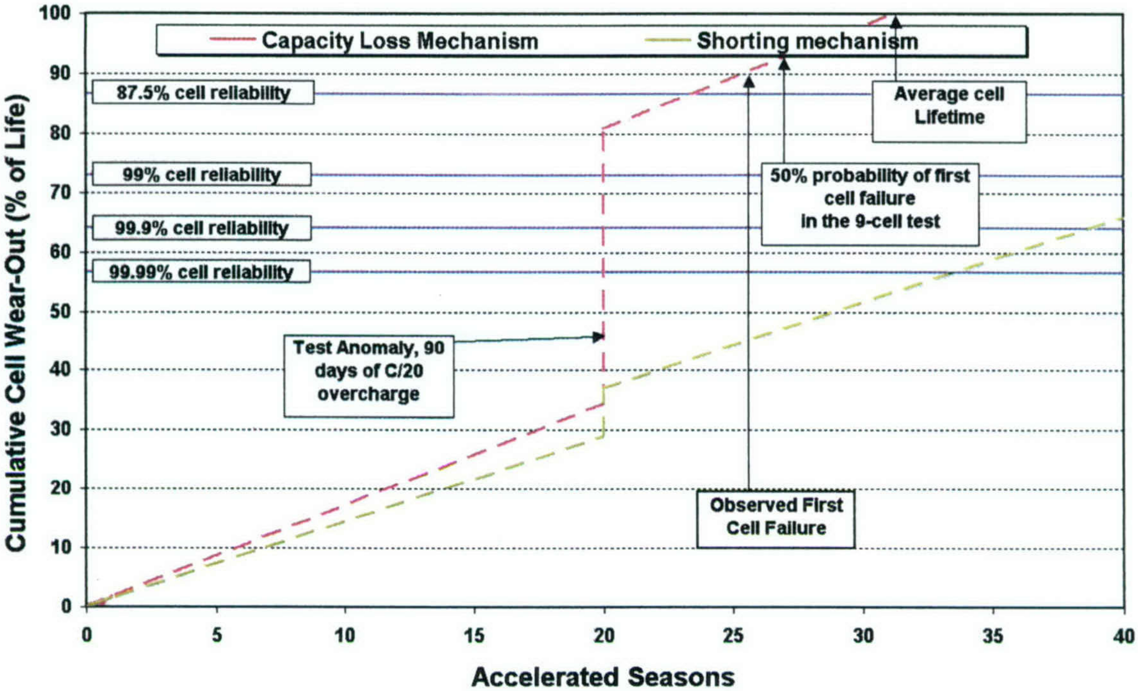


Figure 2. The predicted accumulation of wear based on the model of Ref. 1 during the test timeline for a 9-cell accelerated GEO ground test of 4.5-in.-dia nickel-hydrogen cells at 91.6% DOD.

The results of this test can be correlated with the model predictions, providing the results in Figure 3. The model predicts that after 30 seasons of operation, there was less than a 0.02% probability of

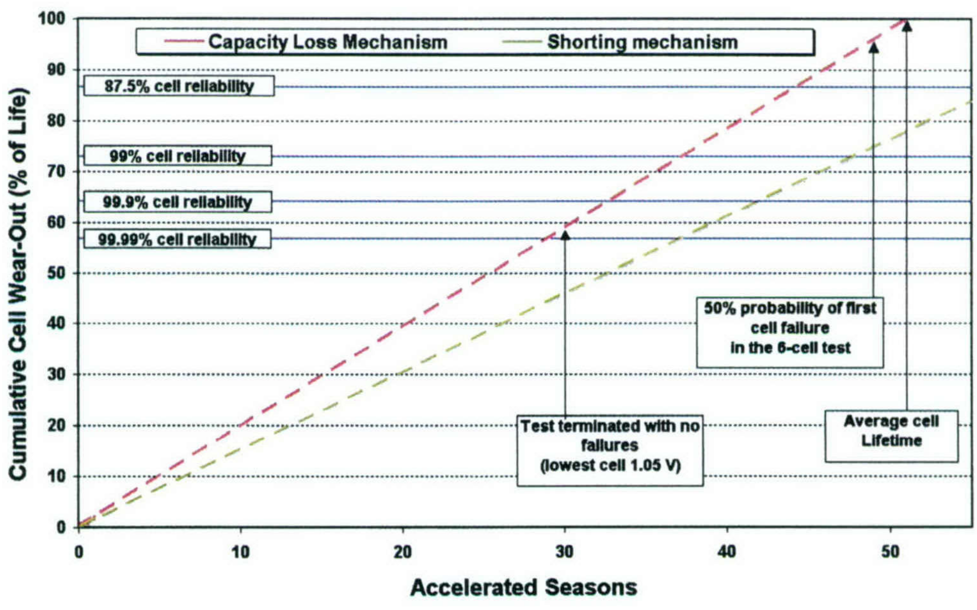


Figure 3. Correlation of model predictions of accumulated wear with test results for a 6-cell test of 4.5-in.-dia nickel-hydrogen cells at 91.2% DOD (based on nameplate).

experiencing a cell failure as a result of capacity loss, and failure due to short-circuiting was several orders of magnitude less probable. The model also predicts an average cell lifetime of 51 seasons in this test, and that about 48 seasons are needed to accumulate enough wear to get over a 50% probability of having one cell fail. Since the test was not run to failure, it is not possible to quantify the comparison between the model prediction and the test results. However, clearly the model prediction is fully consistent with the test results.

Accelerated life tests have also been performed on numerous 3.5-in.-dia nickel-hydrogen cells that typically are in the 50–90 Ah capacity range. One example of such a test on a 23-cell pack run at 82.3% DOD based on nameplate capacity (70% based on actual +5°C capacity) is indicated in Figure 4. This pack involved repeated 44-day eclipse seasons, with 2-week solstice seasons during which the cells were on continuous trickle charge. Recharge was at about a C/15 rate to a recharge fraction of 1.20, after which the C/100 trickle charge rate was applied. These cells operated for 39 accelerated seasons before the test was stopped with all cells still operating (the lowest was at 1.05 V during the longest eclipse).

The model can be used to predict the rate at which cell wear accumulated during this test, providing the results in Figure 4. Interestingly, the model predicts that failure is most likely under these conditions from short-circuiting, but was still unlikely after the 39 seasons that were completed. The model predicts a 50% probability of the first cell failing after 44–45 seasons, and an average cell life time of 56 seasons. Because short-circuiting is not commonly seen as a failure mode in GEO tests, there may be some question regarding the accuracy of the short-circuit failure mode model in the GEO environment. However, the test of Figure 4 was not run long enough to provide any quantita-

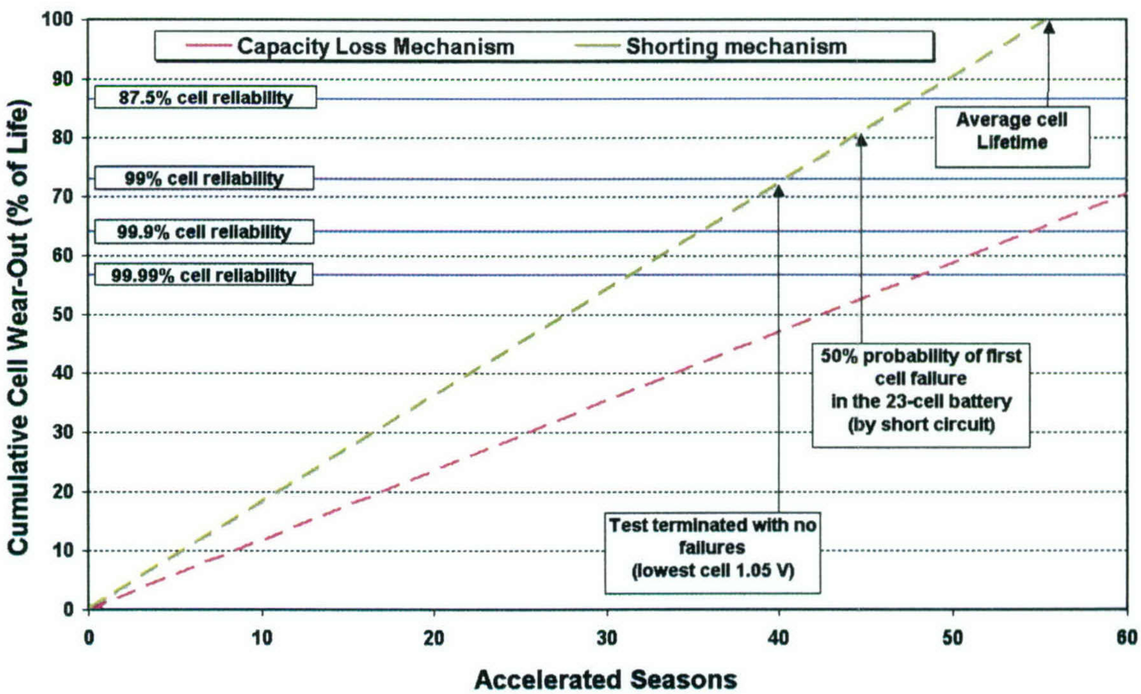


Figure 4. Correlation of model predictions of accumulated wear with test results for a 23-cell test of 3.5-in.-dia nickel-hydrogen cells at 82.3% DOD (based on nameplate).

tive check on whether the predicted short circuits would have actually materialized. The results of this test are consistent with the model prediction. In terms of capacity loss degradation alone, this test would have had to run well over 60 seasons before a capacity-loss failure would be anticipated.

### 2.2 Correlations with Orbital GEO Performance

The longest GEO orbital nickel-hydrogen battery performance data for the Mantech-type cells commonly used today covers about 15 years of operation at depths of discharge in the 55–60% range. These cells are continuing to perform adequately, showing no evidence of significant degradation or impending cell failure. Additional nickel-hydrogen batteries have been operating in a number of orbiting satellites for periods that range up to 15 years, again with no reports of any cell failures resulting from normal wear-related processes in properly designed cells. Therefore, such orbital data simply imposes a lower limit on the lifetimes of the cells for each set of operating conditions. The lower limit will continue to increase as additional orbital data are accumulated in the coming years.

The life model may be correlated with this orbital database for several instances to evaluate whether the model predictions are consistent with the presently available data. The first correlation that will be examined is for the longest GEO performance of about 15 years. The peak DOD in this case is about 60%, the battery operating temperature approximately 0°C, the peak charge current is C/12 to a recharge fraction of about 1.20, and the trickle charge rate is ~C/150. The peak cell recharge voltage runs about 1.56 V under these conditions. For these battery operating conditions, the wear model predicts the accumulation of wear indicated in Figure 5. The model predicts that about 34 years of operation are needed before there is a 50% probability of a cell failing in a 22-cell battery, and that

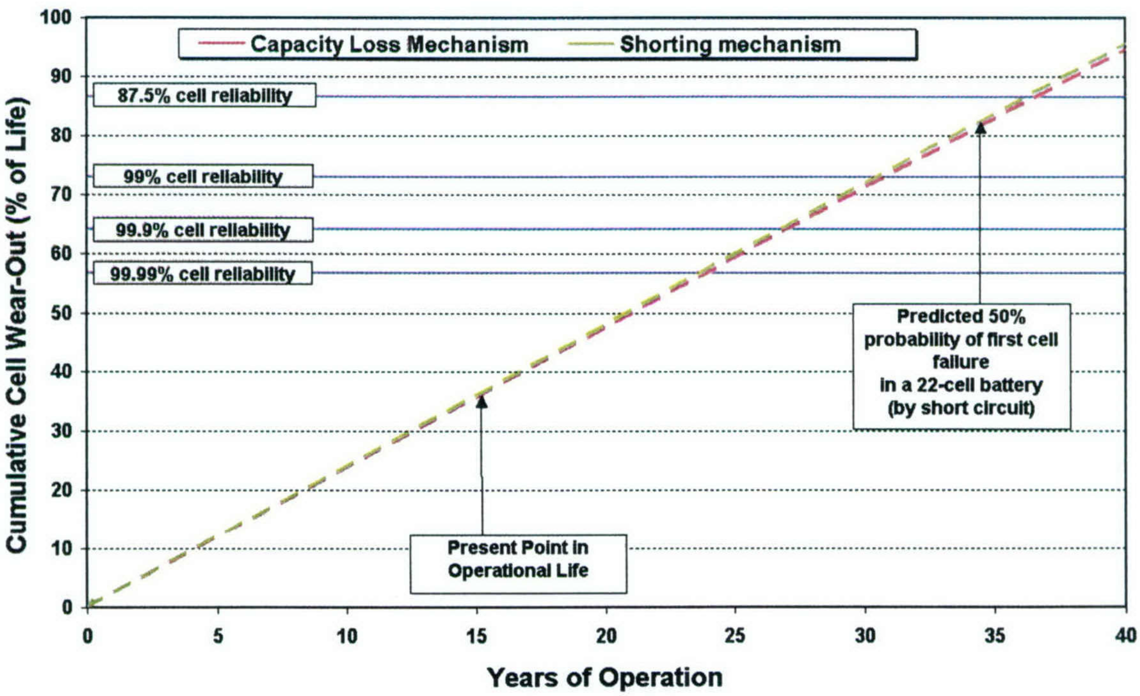


Figure 5. Accumulation of wear predicted by the wear model for a GEO nickel-hydrogen battery that presently has about 15 years of operating time at a peak of 60% DOD.

this failure is equally likely to occur as a result of capacity degradation or a short circuit. Clearly this prediction agrees with the observed performance out to about 15 years, which is predicted to have only consumed about 40% of the mean cell lifetime. A number of years of continued battery operation will be required before these cells can provide a more quantitative correlation with this model.

A second example that can be used to compare orbital experience with the model predictions has been chosen to specifically examine the model predictions when a significantly higher trickle charge rate (C/100) is used. It is generally agreed that this is an excessive trickle charge rate for low-temperature battery operation, where the self-discharge rate of all cells is much lower than even C/200. However, the increased stress and battery wear that accompanies the higher trickle charge may be somewhat offset by the tendency for the higher trickle charge rate to keep all the cells balanced at a higher state of charge (typically estimated at 110% of nameplate capacity at beginning of life) for operation at temperatures below 0°C. This added capacity can specifically be included in the model predictions.

The second GEO example involves a satellite that uses a C/100 trickle charge rate, about a 53% DOD, a battery operating temperature of about 0°C, a recharge fraction (at about a C/12 rate) of 1.10, and a peak cell recharge voltage of about 1.54 V. This satellite has been operating with no battery problems for 12 years. Figure 6 shows the model predictions of the wear accumulated on these battery cells and their predicted lifetime. A 50% probability of seeing a cell failure in a battery is predicted between 17 and 18 years of life, which is well beyond the present lifetime of 12 years. This failure is expected to occur as a result of a short circuit rather than capacity loss, although the probability of failure by capacity loss is nearly as high as the probability of a short circuit. Because these

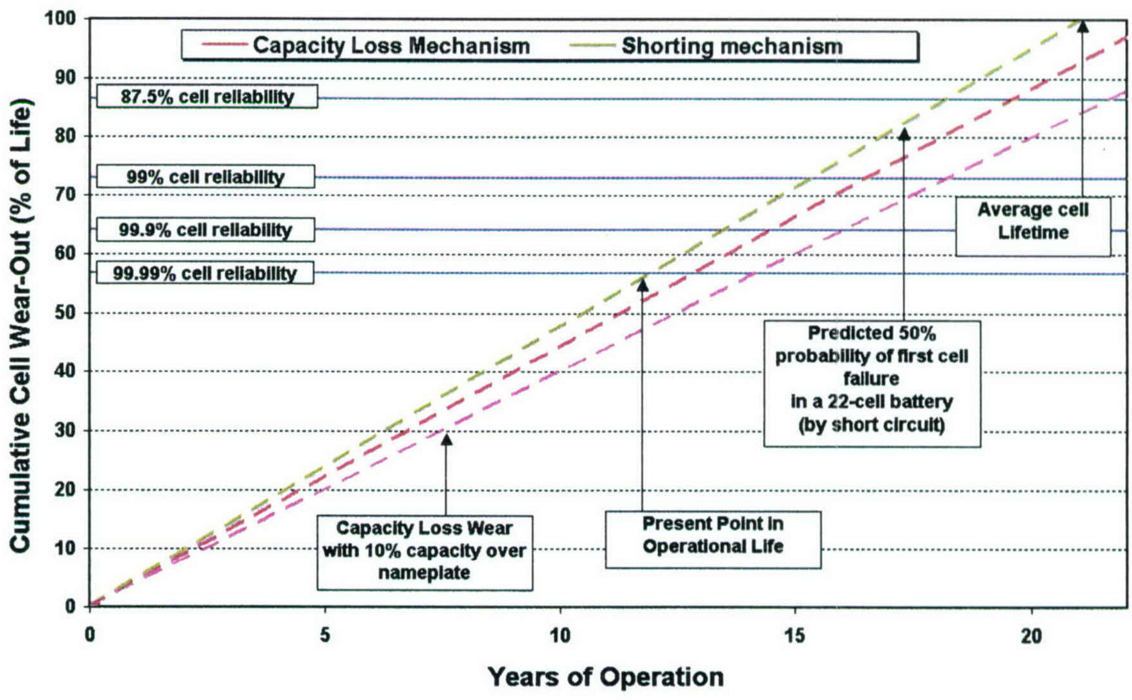


Figure 6. Wear accumulation predicted by the model for nickel-hydrogen batteries operating in GEO at 53% DOD and 0°C, presently with 12 years of good orbital performance. The lowest line indicates wear when 10% extra BOL capacity over nameplate is assumed.

cells are operating at low temperature with a high trickle charge rate, the model may also reasonably be run assuming 10% capacity over nameplate at the beginning of life. With this assumption, the lower line in Figure 6 is obtained for failure by capacity loss, which could add another 1–2 years of predicted life to the cells if they were not first predicted to fail by short-circuiting. The short-circuit failure mode is not highly dependent on cell DOD or capacity margin.

Again, we appear to have an insufficient duration of orbital data to quantitatively address the key issue of how higher trickle charge currents actually should be counted in overcharge-induced stress for modeling either short-circuit or capacity loss failure modes in GEO. The example of Figure 2 validates the generalized use of this model for GEO eclipse season operation and overcharge rates of C/20 or greater. However, when the trickle charge rate drops to C/50 or C/100, or even lower, does the rate dependence included in the model (and based on higher currents) accurately describe the changes in overcharge stress? At present, we have insufficient long-term data to definitively answer this question. The real question that must be answered to further refine the model is: what is the proper method for defining the thresholds where low charge rates stop contributing to overcharge-induced wear? The present model gives a threshold that is somewhat higher than the self-discharge rate, and is based on trend analysis for a significant body of LEO data. This threshold behavior is indicated in Figure 7 for the capacity loss degradation mode. However, the LEO data do not include extremely low rate overcharge (C/50 or lower), and therefore do not rule out alternative functions defining these thresholds and how the wear rate approaches the thresholds for different operating conditions.

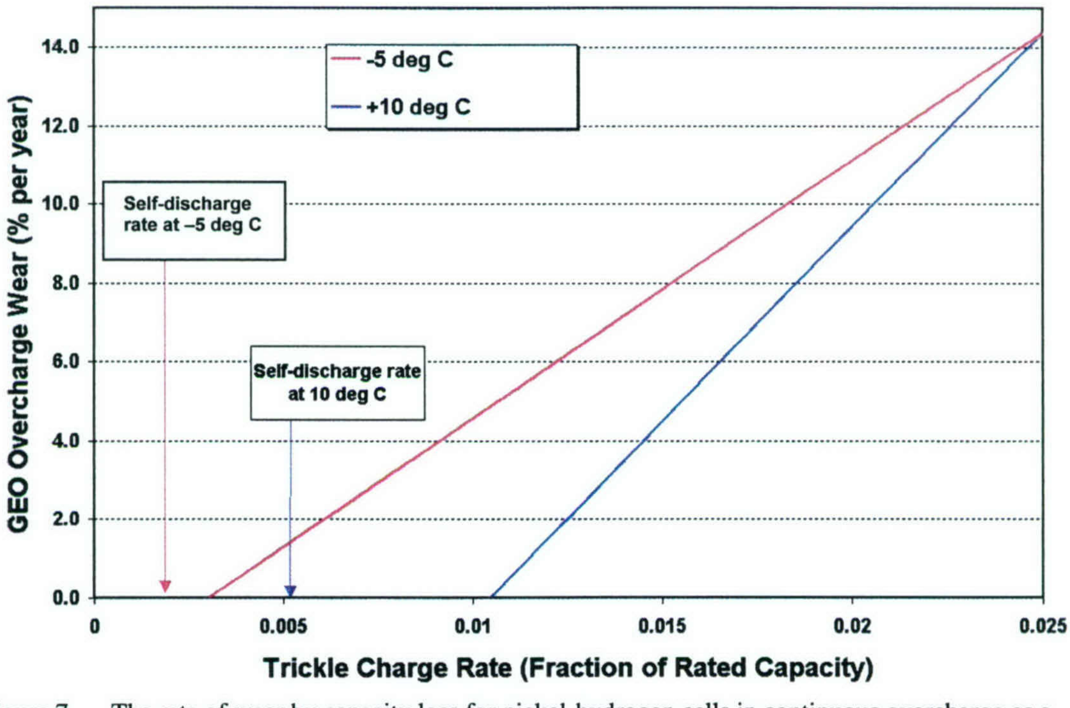


Figure 7. The rate of wear by capacity loss for nickel-hydrogen cells in continuous overcharge as a function of overcharge rate. The wear includes degradation from the amount of excess overcharge and from the rate of overcharge. Note that the wear threshold is significantly above the self-discharge rate.

However, the model in its present form appears to be consistent with both the GEO orbital data and the accelerated GEO ground test data that are available. Therefore, it appears appropriate to use the model in its existing form until actual data are obtained indicating that it needs to be modified, which will require a number of years of further orbital experience with nickel-hydrogen batteries. However, it must also be recognized that while this model is consistent with the available GEO data and seems to accurately capture wear in accelerated GEO tests, it has not been quantitatively validated for real-time GEO nickel-hydrogen battery life by a source of independent data.

## 3. Generalized GEO Nickel-Hydrogen Battery Life Projections

The model described in Ref. 1 and discussed in the preceding section for application to GEO battery operation, can be used to evaluate the known sensitivities of nickel-hydrogen batteries to the operational conditions and environments encountered in GEO usage. In particular, we will be examining the effects of overcharge and trickle charge, as well as different operational temperatures, and lifetime differences due to how the battery capacity is rated.

The model used here is based on a significant body of test data that strongly supports the idea that overcharge is the single greatest source of stress contributing to the wear out of nickel-hydrogen cells. In this context, overcharge includes a wear contribution associated with the amount of excess overcharge, as well as a contribution associated with the rate of the overcharge. However, the model also demonstrates that nickel-hydrogen cells are extremely robust, and can tolerate very significant levels of overcharge and provide very long life before they wear out. In GEO applications, the trickle charge can be the largest factor contributing to accelerated wear out if a trickle charge rate is used that is significantly greater than the wear threshold current. For this reason, we have analyzed the effect of different trickle charge rates on the expected lifetime of nickel-hydrogen cells in GEO operation.

The baseline conditions used in this analysis are 76% DOD, a temperature of –5°C around the eclipse seasons with warming to +8°C at the mid-solstice, a 1.54 peak cell recharge voltage, a C/12 peak recharge rate, and a 1.15 recharge fraction before switching to trickle charge after each eclipse. The DOD is based on nameplate cell capacity unless otherwise stated. With these conditions, the GEO cell wear projection indicated in Figure 8 is obtained. With a C/100 trickle charge rate, the cells are predicted to fail as a result of insufficient capacity, with a 50% probability of a cell failing in a 22-cell battery after about 16 years of operation.

As expected, much of the wear in Figure 8 results from the trickle charge accumulated during the long solstice periods. The strong contribution of trickle charge to wear is illustrated in Figure 9, where the battery cell lifetime is plotted as a function of DOD with either a C/100 or a C/200 trickle charge current. The steeply sloping portions of the lines in Figure 9 at higher DOD result from capacity loss being the life-limiting failure mode, while the relatively flat linear regions at lower DOD result from short-circuiting being the expected life-limiting failure mode. It is apparent from Figure 9 that eliminating un-needed trickle charge can significantly increase the expected lifetime of nickel-hydrogen cells.

The issue of the needed rate of trickle charge is closely linked to the concept of capacity walk down. As a battery goes through a GEO eclipse season, the capacity will walk down somewhat during the longest eclipses of the season, and then recover as the eclipses shorten and the DOD decreases. At high operating temperatures (i.e., 10°C), trickle charge rates as high as C/100 are needed to limit the capacity walk down and to compensate for a relatively high self-discharge. Because the self-discharge is relatively high, there may actually be very little excess overcharge and wear during higher temperature operation with a C/100 trickle charge rate. However, at low temperatures, a

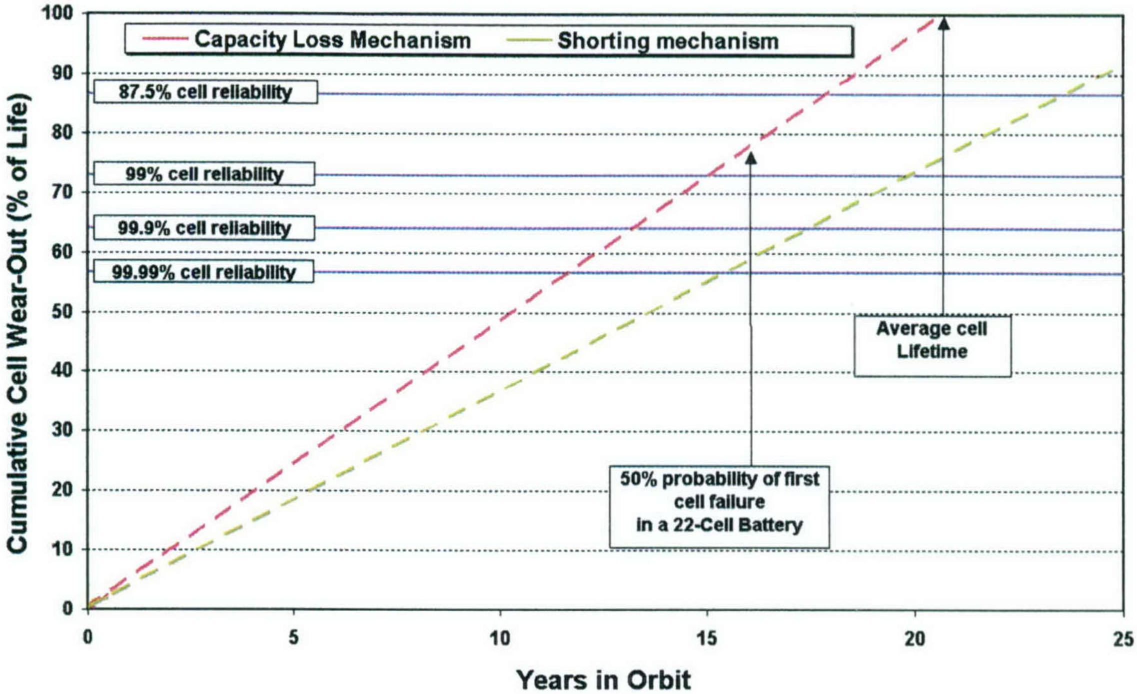


Figure 8. Projected wear-out timeline for baseline 76% DOD GEO conditions with a C/100 trickle charge rate.

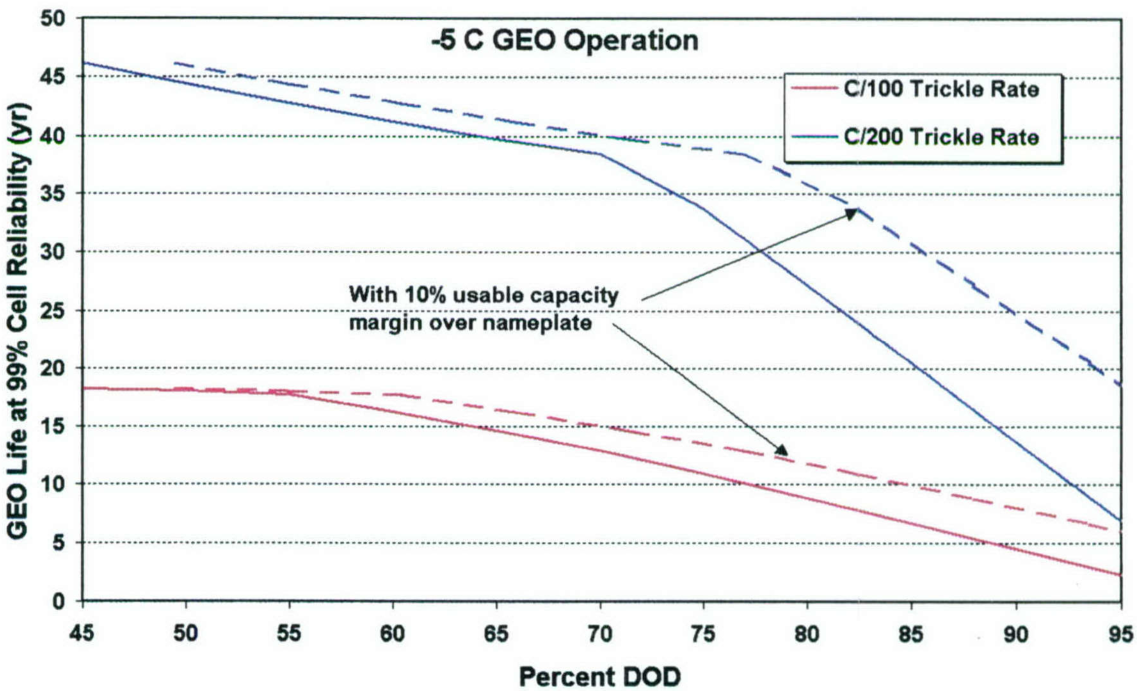


Figure 9. Predicted cell lifetime as a function of DOD during GEO operation with different trickle charge rates. The solid lines base the DOD on nameplate cell capacity, while the dashed lines assume 10% capacity over nameplate in calculating the DOD.

C/100 trickle charge rate prevents any significant walk down of capacity, but also contributes a large amount of excess overcharge that can accelerate cell wear. This is the primary reason for the difference in life predicted for the different trickle charge rates in Figure 9.

An added point that is illustrated in Figure 9, is the role that extra capacity margin can play in a nickel-hydrogen cell. If a nickel-hydrogen cell can be maintained precisely at its nameplate capacity at beginning of life as it goes through an eclipse season, the solid curve predictions in Figure 9 apply. However, nickel-hydrogen cells are sometimes built with 10–20% extra capacity margin above the nameplate capacity. If this margin can be maintained through an eclipse season against capacity walk down, then an extra usable margin exists, as is illustrated by the dashed curves in Figure 9. Typical extra capacity margin levels are about 10% (as shown in Figure 9), which can add 2–5 years to the battery lifetime at high depths of discharge. Conditions that aid in maintaining the capacity margin and reducing capacity walk down are low-temperature operation (which aids in maintaining high charge efficiency) and higher trickle charge rates. However, excessive trickle charge can significantly increase degradation as a consequence of keeping the battery pumped up to a very high capacity.

The battery operating temperature is also very important in its influence on capacity maintenance and the rate of performance degradation. It is normally thought that reduced temperatures lower the rate of the degradation processes in battery cells. However, there are other factors that can dominate the direct effect of temperature that is typically expected. Figure 10 shows the effect of temperature on nickel-hydrogen battery life predicted for GEO operation with either a high or a low trickle charge rate. At low temperatures (solid curves in Figure 10) the lifetime of a cell is highly sensitive to the trickle charge rate and the amount of overcharge. This is primarily a consequence of the cell not needing much overcharge at low temperatures to counter self-discharge; therefore, nearly all overcharge contributes to wear, particularly with the C/100 trickle charge rate. At higher temperatures, the cell lifetime is much less sensitive to the trickle charge rate. The higher temperature actually adds more than 5 years of life for the C/100 trickle charge conditions, while for the low trickle charge rate the lifetime is reduced by 2–5 years by increased temperature for the conditions of Figure 10.

It is clear from this analysis that it is important to consider both the expected rate of degradation and the cell capacity in selecting both the operating temperature and the charge control method for nickel-hydrogen cells. Specifically, a trickle charge rate that is appropriate for the operating temperature of the cells should be selected. Supporting the results of Figure 10 are numerous life tests where cells operating in a colder environment gave significantly lower cycle life than did similar cells operating in a warmer environment.

It is also of interest to examine the effect of temperature on the role of capacity margin in nickel-hydrogen cells. It is generally believed that operating cells at low temperatures can accentuate the importance of having capacity margin above the nameplate cell capacity. Figure 11 provides the model predictions for this situation by comparing predicted cell lifetime for different temperatures and trickle charge rates both with and without 10% above-nameplate capacity margin. The solid lines in Figure 11 show the cell life if the DOD is based on having an extra 10% capacity over the nameplate capacity. In the model, this extra capacity decreases the slope of the drop-off in life at high depth of discharge that arises from the cell capacity degradation. The reason for the decreased slope

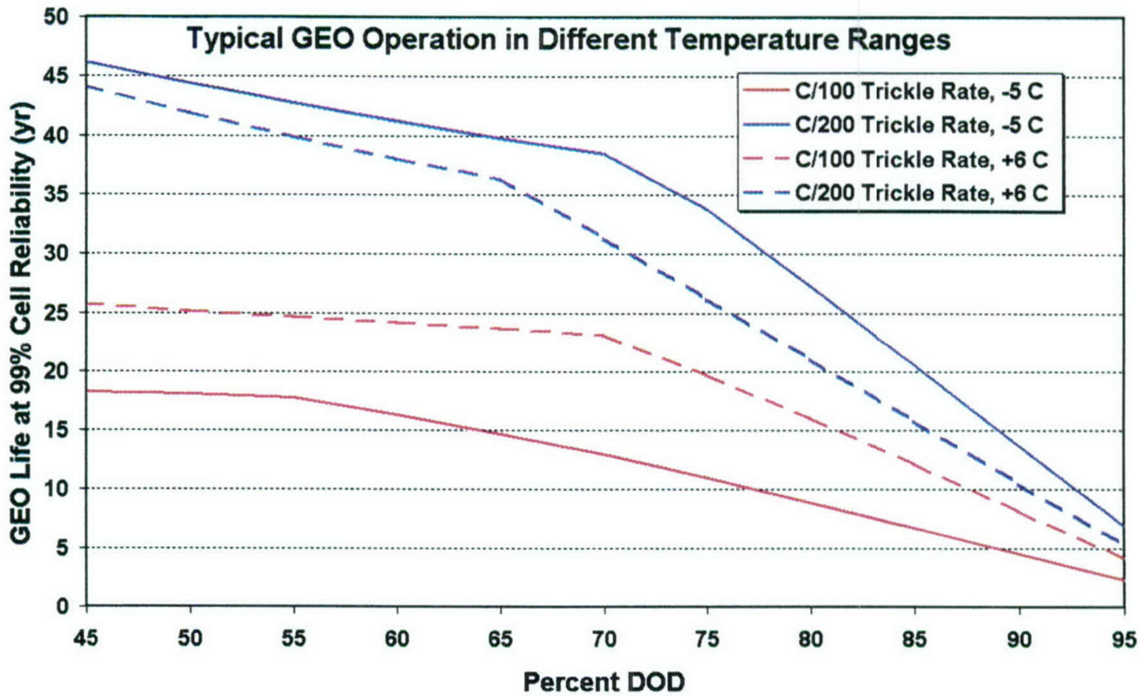


Figure 10. Predicted cell lifetime at low and high operating temperatures with different trickle charge rates, as a function of DOD based on nameplate capacity.

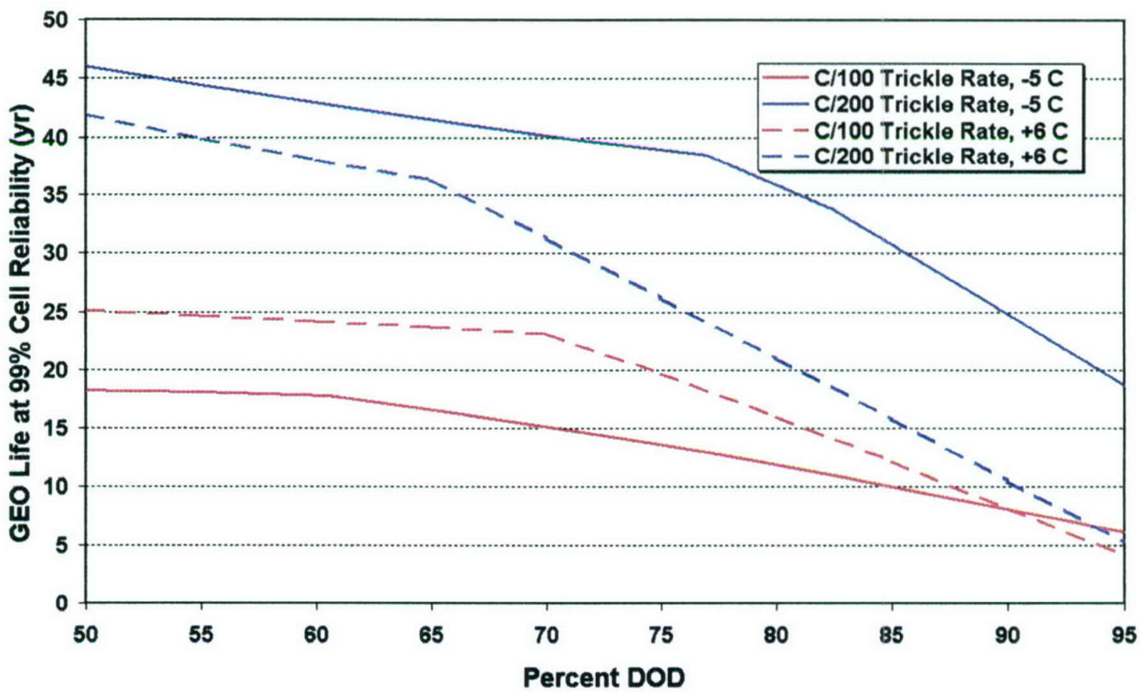


Figure 11. Nickel-hydrogen cell lifetime with and without 10% capacity margin over the nameplate cell capacity. The solid lines are for a cell with 110% of nameplate capacity, while the dashed lines are for a cell with 100% of nameplate capacity.

is that with the extra 10% capacity, the cell will give zero life at 110% DOD based on nameplate capacity rather than at 100% DOD. Thus, if it can be assured that the extra capacity will be available at the beginning of life, a significant extension of cell life can be realized for higher DOD operation where capacity degradation is most likely to limit cell lifetime.

The range of nickel-hydrogen battery life that is predicted for the different charge control parameters being used in existing satellite electrical power systems is illustrated in Figure 12. Also shown in Figure 12 is the range of operating life accumulated for typical satellites having the most years in operation at low battery temperatures. The most noteworthy observation in Figure 12 is the tremendous range of life that is predicted for nickel-hydrogen batteries for different methods of charge control. Battery life margin can be extended by at least a factor of 2 over the typical 15-year GEO life requirement by optimizing the charge control system.

While the lifetime capability of nickel-hydrogen batteries is predicted to be well in excess of 30 years with a reasonably optimized charge control system, it should be noted that the predicted lifetime up to about 65% DOD is reasonably consistent with the typical 15-year GEO satellite design life, as long as the trickle charge rate is not too high. Of course lifetime margin is quite important for assuring high reliability, and for this reason, it is important to consider minimizing unnecessary stress on the batteries that could reduce the cell lifetime.

Figure 13 shows how the predicted battery lifetime increases if it is assumed that there is 10% extra usable capacity in the cells above their nameplate capacity. At the typical DOD levels shown for the points in Figures 12 and 13, the extra capacity allows about a 5% increase in the DOD while keeping

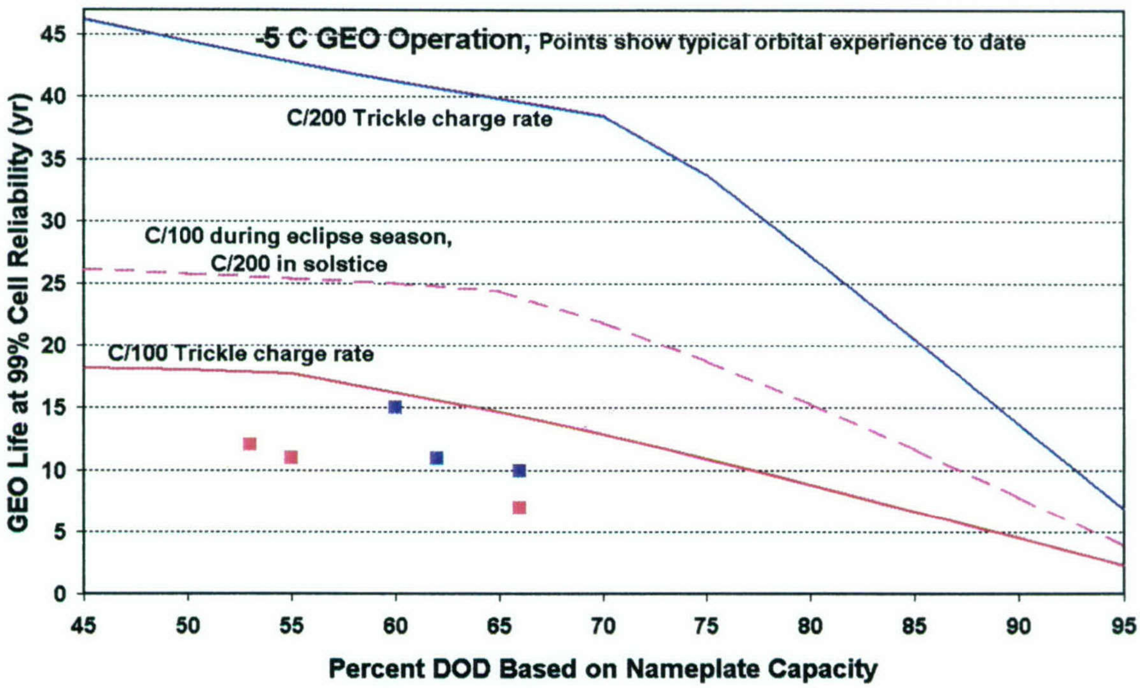


Figure 12. Model predictions for various charge control methodology for cold-biased nickel-hydrogen cells, along with comparisons to typical orbital battery experience to date.

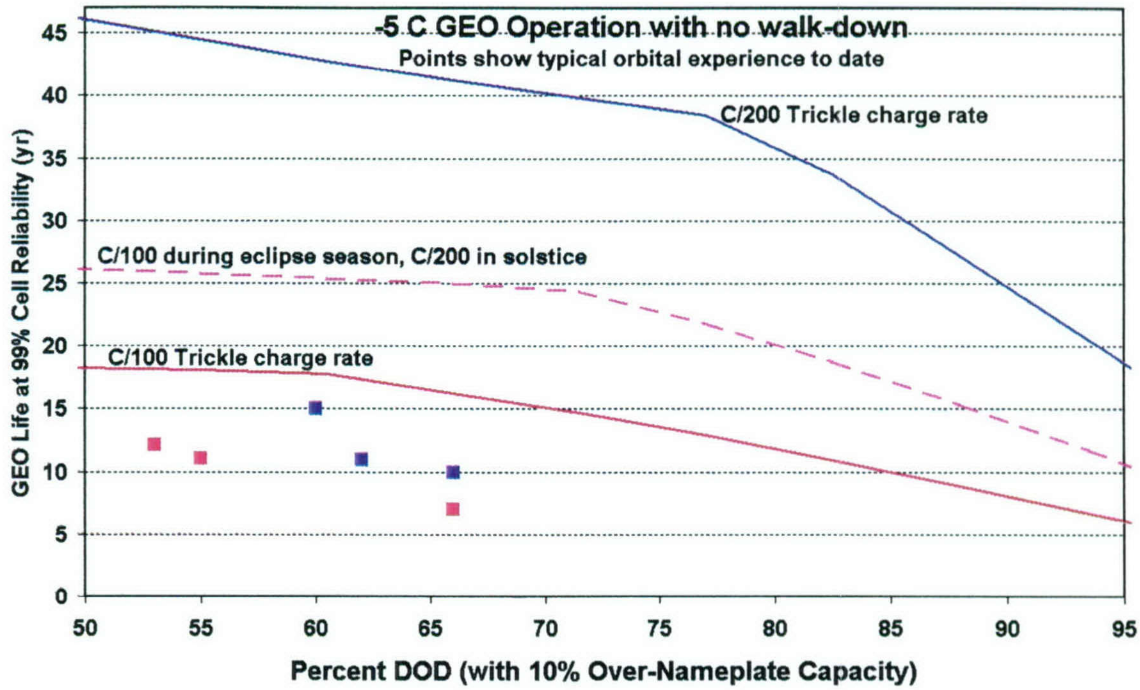


Figure 13. Model predictions for various charge control methodology for cold-biased nickel-hydrogen cells, along with comparisons to typical orbital battery experience to date, assuming the cells have 10% usable capacity over their nameplate rating.

the same predicted lifetime, or about a 2-year increase in predicted lifetime at an fixed DOD (in the 60-70% DOD range).

Unfortunately, the model used here to predict battery life does not include the different amounts of capacity walk-down experienced at different temperatures or trickle charge rates as the battery cells age. Capacity walk-down is caused by a decrease in charge efficiency that invariably occurs as the battery cells age. The magnitude of the capacity walk-down can be estimated from our test experience and from first-principles cell performance models. If we include reasonable estimates for capacity walk-down for the results in Figure 13, the prediction in Figure 14 is obtained for low-temperature operation. From Figure 14, it is clear that capacity walk-down effects are accentuated at low trickle charge rates, and at high depths of discharge (>87% DOD) can make the life at a C/200 trickle charge rate less than that with a C/100 trickle charge rate. The use of a C/200 trickle charge rate during the solstice periods, when some walk-down can be tolerated, in conjunction with a C/100 trickle rate during eclipse seasons (which minimizes walk-down), can provide significantly improved life expectancy. The combination of low stress and minimal capacity walk-down makes this dual trickle charge mode of operation particularly attractive for high DOD applications, for which a 99% cell-level reliability can be maintained for 15 years at 87% DOD.

A noteworthy observation that can be made from Figures 12 through 14 is the large disparity between the longest operating orbital battery lifetimes to date (indicated by the points in Figures 12 through 14), and the predicted lifetime to cell failure. The batteries running with the higher trickle charge rates (red points) are today about 5 years short of their predicted life. The batteries running with

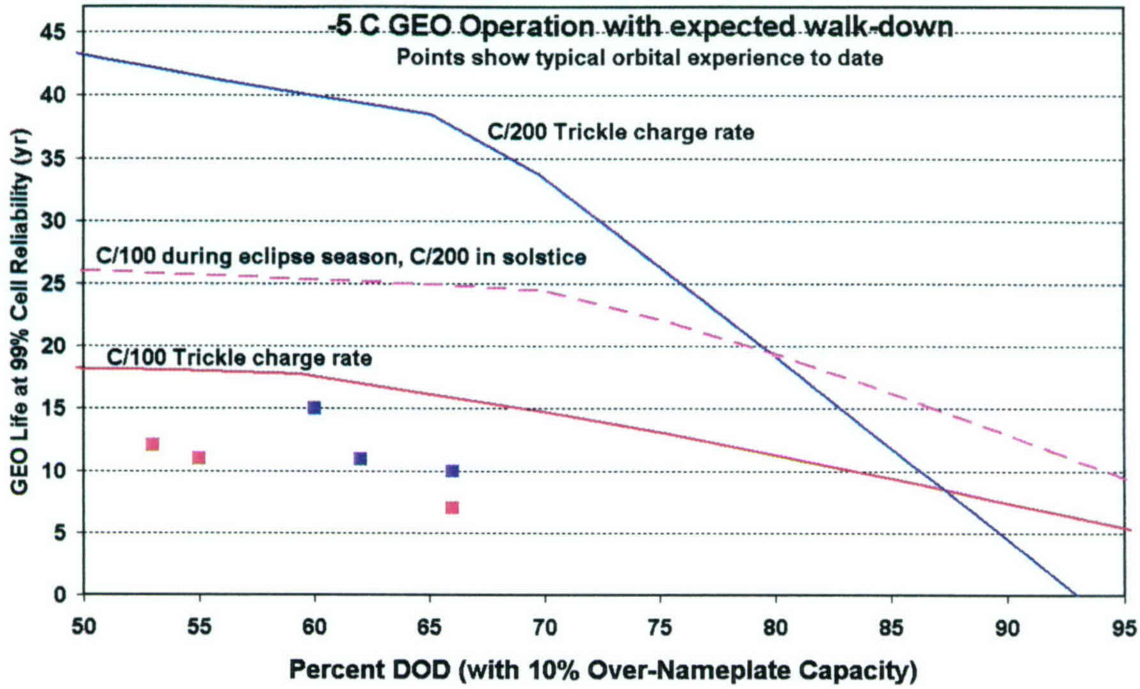


Figure 14. Model predictions of life for cold-biased nickel-hydrogen cells, along with comparisons to typical orbital battery experience to date, assuming the cells have 10% usable capacity over their nameplate rating, and that they undergo typical capacity walk-down behavior over life.

lower trickle charge rates (blue points) are still over 20 years short of their predicted life. This situation clearly makes it difficult to quantify the accuracy of the model for predicting lifetime since we will not really have the needed data for another 5–10 years, assuming these satellites continue to operate long enough to test the battery lifetime prediction.

The data and the predictions in Figures 12 through 14 also illustrate the remarkably long life capability of nickel-hydrogen batteries. The calendar-life capacity wear rate used in this model follows an exponentially increasing dependence (Arrhenius dependence) on temperature, and is about 0.94% per year for 10°C operation, and about 0.59% per year for –5°C operation. While the model used here has a calendar life term that will ultimately limit battery lifetime if other sources of wear are sufficiently low, it is uncertain how accurately the calendar life degradation coefficient is known for GEO operation out to 30 years or more since this coefficient was derived from LEO test data of 10–12 year calendar life duration.

## 4. Conclusions

A model for predicting nickel-hydrogen battery lifetime in LEO orbit applications has been extended to the conditions encountered in GEO orbiting satellites. The model has been found to accurately reproduce the lifetimes observed from available accelerated GEO tests, and is also consistent with the existing orbital performance data. While no known wear-related failures have been yet observed in orbit for nickel-hydrogen cells, there have been a number of on-orbit failures resulting from improper cell design, manufacturing process problems, and improper battery management. Lifetime limitations resulting from these types of non-wear-related failures are not covered by the predictions of this model.

The model has been used to predict how properly designed and operated nickel-hydrogen battery lifetimes should depend on the operating environments and charge control methods typically used in GEO operation. Lifetime is found to be strongly dependent on DOD (particularly at high operating DOD levels), amount of overcharge, trickle charge rate, and operating temperature. In addition, the model finds a strong coupling between these wear-controlling parameters. The model suggests that with an optimized charge control system and optimized operating conditions, properly designed nickel-hydrogen batteries are capable of reliably providing over 30 years of GEO operation at a DOD of 70–75%. The results also indicate that careful optimization of charge control, operating temperature, and the maximum required DOD are needed to guarantee reliable operation beyond 10 years.

## Reference

1. Zimmerman, A. H. and M. V. Quinzio, *Model for Predicting the Effects of Long-Term Storage and Cycling on the Life of $NiH_2$ Cells*, Proc. of the 2003 NASA Battery Workshop, 20 November 2003, Huntsville, AL.

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